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Citation: AIP Conference Proceedings **1642**, 346 (2015); doi: 10.1063/1.4906690
View online: http://dx.doi.org/10.1063/1.4906690
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1642?ver=pdfcov
Published by the AIP Publishing

Herschel/HIFI Line Surveys: Discovery of Interstellar Chloronium (H_2Cl^+)

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Abstract. Prior to the launch of *Herschel*, HCl was the only chlorine-containing molecule detected in the interstellar medium (ISM). However, chemical models have identified chloronium, H_2Cl^+, as a relatively abundant species that is potentially detectable. H_2Cl^+ was predicted to be most abundant in the environments where the ultraviolet radiation is strong: in diffuse clouds, or near the surfaces of dense clouds illuminated by nearby O and B stars. The HIFI instrument on *Herschel* provided the first detection of H_2Cl^+ in the ISM. The 2_{12}–1_{01} lines of ortho-$H_2{}^{35}Cl^+$ and ortho-$H_2{}^{37}Cl^+$ were detected in absorption toward NGC 6334I, and the 1_{11}–0_{00} transition of para-$H_2{}^{35}Cl^+$ was detected in absorption toward NGC 6334I and Sgr B2(S). The derived HCl/H_2Cl^+ column density ratios, ~1–10, are within the range predicted by models of diffuse and dense Photon Dominated Regions (PDRs). However, the observed H_2Cl^+ column densities, in excess of 10^{13} cm^{-2}, are significantly higher than the model predictions. These observations demonstrate the outstanding spectroscopic capabilities of HIFI for detecting new interstellar molecules and providing key constraints for astrochemical models.

Keywords: Astrochemistry— ISM: abundances —ISM: molecules — Line: identification —Molecular processes — Submillimetre: ISM
PACS: 95, 98

HERSCHEL/HIFI LINE SURVEYS

The submillimeter band, broadly defined as a decade of wavelengths between 1 mm and 100 μm, gives access to cold, dust enshrouded objects that are often hidden from view at shorter wavelengths. Dust continuum sources with temperatures of order 30 K peak near 100 μm. In colder sources, such as prestellar cores before the onset of star formation, the emission is shifted to even longer wavelengths. A complex network of chemical reactions takes place in these cold environments, including both gas-phase and grain-surface processes. High-resolution heterodyne techniques provide velocity-resolved ($R\sim10^6$) spectra of the rotational lines of abundant gas-phase molecules. Such observations give invaluable information about the chemical composition, kinematics (infall, outflow, rotation) and the physical conditions (temperature, density, UV field intensity, ionization fraction) at the onset of star formation. The line forest of heavy organic species that dominates the line spectrum at longer millimeter wavelengths gradually gives way to fundamental rotational transitions of light hydrides and deuterides in the submillimeter. Atomic fine structure lines of abundant elements: C, O, and N are also present and are important coolants of the gas.

The Herschel Space Observatory [1] is the fourth ESA cornerstone mission, the first space facility to completely cover the 60–670 μm spectral range. It consists of a 3.5-m diameter telescope, passively cooled to ~80 K, in a Lissajous orbit around the Lagrangian point L2, behind the Moon—a very stable and low-background orbit. The satellite was launched by Ariane 5 on May 14, 2009 from the Centre Spatial Guyanais in Kourou, French Guiana. It carries three cryogenically cooled instruments: two imaging cameras, PACS and SPIRE, both using bolometer detectors, and the heterodyne instrument, HIFI.

HIFI [2] covers the wavelength range 625–240 μm using state-of-the art SIS mixers, as well as 212–157 μm using HEB mixers. The instrument has a wide instantaneous IF bandwidth (4 GHz in two polarizations for SIS mixers and 2.4 GHz in two polarizations for HEB mixers), high frequency resolution (1 MHz over the full IF band and up to 140 kHz over a portion of the band), and near-quantum limit sensitivity.

The HIFI science can be broadly described as the "Life Cycle of Gas and Dust". One of the main science themes are unbiased spectral line surveys, which provide a complete census of molecules in star-forming regions. Submillimeter wavelengths give access to high-energy transitions, excited only in the immediate vicinity of the newly forming stars, where a complex, high-temperature chemistry is driven by molecules evaporated from grain

Proceedings of the International Conference of Computational Methods in Sciences and Engineering 2010 (ICCMSE-2010)
AIP Conf. Proc. 1642, 346-349 (2015); doi: 10.1063/1.4906690

mantles (e.g., methanol). HIFI observations thus allow ascertaining the relative importance of the grain-surface and gas- phase chemical processes, the relevant time-scales and the dependence of the chemistry on the source mass, luminosity, etc. In addition, the unbiased nature of these surveys offers an opportunity to detect new species of astrophysical importance.

The fundamental rotational transitions of light hydrides and deuterides that dominate the submillimeter spectrum often have very high critical densities and the excited energy levels are difficult to populate at the typical conditions characteristic of the interstellar medium. However, the dust continuum flux steeply increases at short submillimeter wavelengths. This offers an opportunity to probe even relatively diffuse regions, characterized by several magnitudes of visual extinction, by means of absorption spectroscopy. Lines of sight toward distant HII regions, such as Sagittarius B2 in the Galactic center, often intersect several Galactic spiral arms, thus allowing detailed investigations of the physics and chemistry of the foreground gas in clouds with a wide range of physical conditions.

Two Herschel guaranteed time key programs, HEXOS [3] and CHESS [4], are devoted to spectral line surveys. NGC 6334, a nearby (~1.7 kpc) molecular cloud/HII region complex with a FIR luminosity of 2.6×10^5 L_{sun} is one of the high-mass sources studied within CHESS. The source shows a rich, complex molecular emission spectrum (Fig. 1; HIFI band 1a). In addition, several foreground absorption components are present (e.g., 5).

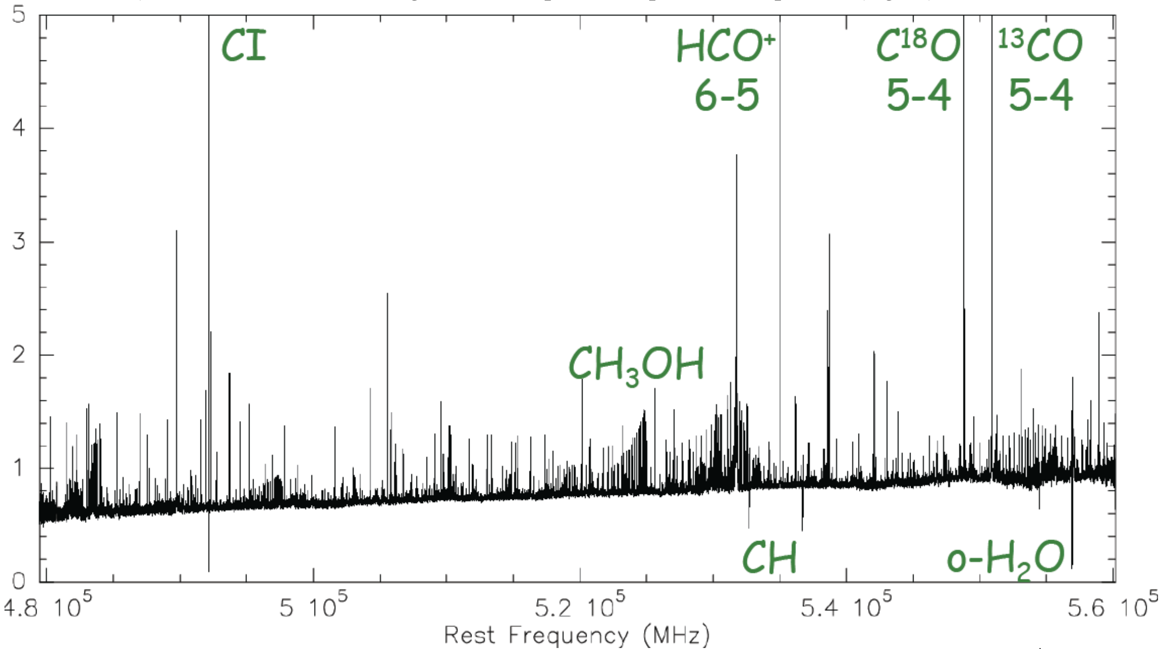

FIGURE 1. HIFI band 1a spectral scan of NGC6334I. Vertical axis is the antenna temperature (T_A^*).

CHLORINE CHEMISTRY IN THE INTERSTELLAR MEDIUM

Chlorine chemistry in the interstellar medium has been studied extensively over the past 35 years [6, 7, 8, 9, 10, 11, 12] and has been recently re-analyzed in preparation for *Herschel* [13]. Prior to *Herschel*, HCl and $H^{37}Cl$ were the only chlorine-bearing molecules detected in the ISM. HCl was first detected toward Orion KL using KAO (14) and subsequently studied in various galactic environments using KAO [17] and ground-based facilities such as CSO [10, 15, 16, and APEX [18].

Recent chemical models of Neufeld & Wolfire [13] have predicted chloronium, H_2Cl^+, to be abundant gas-phase species in Photon Dominated Regions (PDRs), with maximum column densities of a few times 10^{11} cm^{-2}. In dense PDRs, H_2Cl^+ is predicted to be abundant near cloud surfaces (A_V~2), where it is produced in reaction of HCl^+ with H_2. Deeper into the cloud the abundance drops, but it increases again at A_V~10, where HCl^+ abundance is once again enhanced by reaction of H_3^+ with Cl. The 1_{11}–0_{00} transition H_2Cl^+ at 485 GHz, which can be observed simultaneously with the 3_3–1_2 line of O_2, was thus targeted by deep integrations carried out as part of the Herschel Oxygen Project (HOP).

DETECTION OF INTERSTELLAR CHLORONIUM

The unbiased spectral line survey of NGC 6334I provided an opportunity to search for new ISM molecules by means of absorption spectroscopy (see, e.g., the detection of the reactive H_2O^+ cation; [19]). Strong absorption at 781 GHz (Fig. 2) provided the initial identification of H_2Cl^+ [20]. The line was identified as the 2_{12}–1_{01} ground state ortho transition. The equivalent line of ortho-$H_2{}^{37}Cl^+$ at 780 GHz and the ground state para-H_2Cl^+ 1_{11}–0_{00} line at 485 GHz were also identified, blended with dimethyl ether emission features. Supporting observations of the 485 GHz para-H_2Cl^+ transition toward Sgr B2(S) were carried out as part of the HOP program.

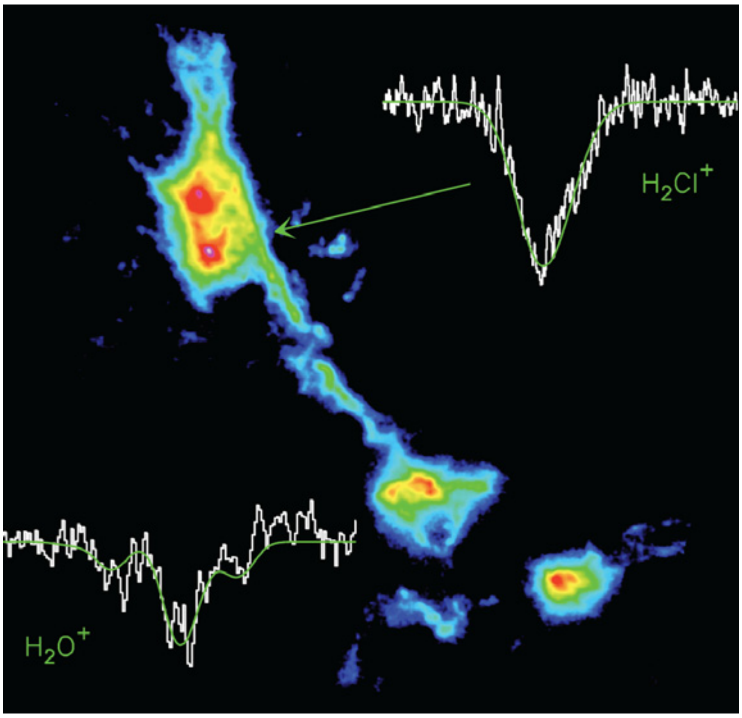

FIGURE 2. Herschel/HIFI spectra of the 2_{12}-1_{01} transition of H_2Cl^+ [20] and the 1_{11}-0_{00} transition of H_2O^+ [19] toward NGC6334I. Background image is the 350 μm dust continuum emission observed with the SHARC II camera on the Caltech Submillimeter Observatory.

The observed column densities of H_2Cl^+ in NGC 6334I and Sgr B2(S) are a few times 10^{13} cm^{-2} [20], two orders of magnitude higher than the PDR model predictions for normal incidence [13]. This may be indicative of limb brightening or the presence of multiple PDRs on the line of sight. The HCl/H_2Cl^+ ratio in a pencil beam toward NGC 6334I and Sgr B2(S) at velocities corresponding to the cloud envelope is ~10, within the range predicted for dense PDR models. The measured HCl/H_2Cl^+ column density ratio in the foreground gas toward Sgr B2(S) at velocities near 0 kms^{-1}, ~1, is also consistent with predictions for diffuse PDR models.

FUTURE PROSPECTS

The 485 GHz para-H_2Cl^+ transition has been observed in a number of HOP sources and the data are currently being analyzed. Models of Neufeld & Wolfire [13] have identified HCl^+ as another abundant gas phase species. Observations of the 1444 GHz transition of this molecule using HIFI are planned. The HCl^+/H_2Cl^+ ratio will provide key constraints for the chemical models. The soon to be commissioned new wideband 230 GHz receiver at the Caltech Submillimeter Observatory will allow ground-based observations of the 189 GHz 1_{10}–1_{01} transition of ortho-H_2Cl^+, which has the same lower level as the 781 GHz line observed with HIFI. Future prospects for observing key gas-phase species important for the chlorine chemistry in the ISM are thus bright and significant observational progress is expected in the coming years.

ACKNOWLEDGMENTS

HIFI has been designed and built by a consortium of institutes and university departments from across Europe, Canada and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands and with major contributions from Germany, France and the US. Consortium members are: Canada: CSA, U.Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfR, MPS; Ireland, NUI Maynooth; Italy: ASI, IFSI-INAF, Osservatorio Astrofisico di Arcetri-INAF; Netherlands: SRON, TUD; Poland: CAMK, CBK; Spain: Observatorio Astronomico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology-MC2, RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University-Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC. Support for this work was provided by NASA through an award issued by JPL/Caltech and by the NSF award AST-0540882 to the CSO.

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